Marine Environment of the Eastern and Central Aleutian Islands

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ABSTRACT

To examine the marine habitat of the endangered western stock of the Steller's sea lion (*Eumetopias jubatus*), two interdisciplinary research cruises (June 2001 and May-June 2002) measured water properties in the eastern and central Aleutian Passes. Unimak, Akutan, Amukta, and Seguam Passes were sampled in both years, and three additional passes (Umnak, Samalga, and Tanaga) were sampled in 2002. In the North Pacific (and to a lesser extent in the Bering Sea), a strong front in water properties was observed near Samalga Pass in June of both years, with significantly warmer, fresher, and more nitrate poor water east of Samalga Pass than west of the pass. These water properties reflect differences in source waters (Alaska Coastal Current versus Alaskan Stream), mixing depth, and Bering Sea influence. Strong cross-Aleutian gradients were also observed with warmer, fresher water on the North Pacific side of the archipelago. The nutrient content of the waters flowing through the passes, combined with the effects of mixing within the passes, influences the transport of nutrients into the Bering Sea. As water moves away from the strong mixing of the passes and becomes more stratified, phytoplankton can take advantage of the enhanced nutrient concentrations. Thus, the northern side of the Aleutian Islands (especially in the lee of the islands) appears to be more productive. Combined with evidence of coincident changes in many ecosystem parameters near Samalga Pass, it is hypothesized that Samalga Pass forms a physical and biogeographic boundary between the eastern and central Aleutian marine ecosystems.

KEY WORDS: Aleutian Passes, Bering Sea, water properties, nutrients, mixing

INTRODUCTION

The Aleutian Islands and their nearby waters are home to important and varied fish stocks as well as to vast numbers of marine birds and mammals, which feed in these productive waters. Among the resident species are Steller's sea lions (*Eumetopias jubatus*), the western stock of which has declined severely in recent decades to the point where it has been classified as endangered. Declines have been particularly severe in the central and western Aleutian Islands (Loughlin and York, 2000). There is evidence that the diets of Steller's sea lions change in the vicinity of Samalga Pass from domination by walleye pollock (*Theragra chalcogramma*) east of the pass to domination by Atka mackerel (*Pleurogrammus monopterygius*) west of the pass (Sinclair and Zeppelin, 2002). Therefore, we examined the hypothesis that there is a fundamental change in the marine habitat that dictates a different ecology for sea lions living on either side of Samalga Pass. The nature of that change was unknown.

The Aleutian passes are the conduit through which the North Pacific and the Bering Sea interact. The flow through the eastern and central passes is dominated by strong tidal currents with a net flow that is primarily northward (Reed and Stabeno, 1994; 1997; Stabeno *et al.*, 2002; Stabeno *et al.*, 2005). The eastern passes (Fig. 1; Table 1) are relatively shallow and have been considered to have little contribution to the net inter-basin transport (Favorite, 1974). However, they may provide nutrients to the southeast Bering Sea shelf through tidal mixing (Stabeno *et al.*, 2002). The sources of water feeding the passes may have important implications in influencing the marine environments of the Aleutian Archipelago and the southeast Bering Sea.

The primary currents in the region consist of the Alaska Coastal Current (ACC), the Alaskan Stream, the Aleutian North Slope Current and the Bering Slope Current (Fig. 1). The ACC is driven by winds and freshwater discharge from the coastal regions around the Gulf of Alaska (Royer, 1979; Royer *et al.*, 1979) and flows southwestward along the south side of the Alaska Peninsula (Hinckley *et al.*, 1991; Reed, 1987; Schumacher and Reed, 1986). Transport and salinity of the ACC exhibit a strong seasonal cycle dictated by seasonal wind patterns and the seasonal cycle of the freshwater inputs around the Gulf of Alaska (Schumacher and Reed, 1980; 1986; Stabeno *et al.*, 2004). The westward extent of the ACC has been assumed to be Unimak Pass (Stabeno *et al.*, 2002). Here, we present evidence that while part of the ACC flows into the Bering Sea through Unimak Pass, a portion of the ACC continues along the south side of the Aleutian Islands until it turns northward into Samalga Pass (~170ºW). The strong freshwater signal of the ACC was not observed west of Samalga Pass.

The Alaskan Stream is the western boundary current of the eastern part of the subarctic gyre. It originates at the head of the Gulf of Alaska and flows southwestward along the shelf break (Favorite, 1967). Near Samalga Pass, the shelf narrows and the Alaskan Stream moves closer to the Aleutian Archipelago. The Aleutian North Slope Current is an eastward flowing current along the north side of the Aleutian Islands and is modified along its path by flow through the passes (Reed and Stabeno, 1999a; Stabeno and Reed, 1994; 2004). The Bering Slope Current (Kinder *et al.*, 1975) is a continuation of the Aleutian North Slope Current as it turns northwestward to follow the shelf break of the eastern Bering Sea (Schumacher and Reed, 1992; Stabeno and Reed, 1994).

Despite the importance of the Aleutian Passes as the connection between the North Pacific Ocean and the Bering Sea, and as habitat for marine birds, mammals and commercially important stocks of fish and shellfish, relatively few studies have been undertaken to understand the physical oceanography within the passes. Favorite (1974) examined the exchange of water between the North Pacific and the Bering Sea along the entire Aleutian-Commander island arc. He found that flow through the passes was highly variable. Existing data were inadequate to quantify the mean net transport through the passes, although he estimated that the eastern passes contributed no net annual exchange between the basins. He suggested that the net flow through the eastern passes was likely to be influenced by the latitude of the main axis of the Alaskan Stream and the longitude of its recirculation into the Gulf of Alaska. As noted above, the ACC has an influence (separate from the Alaskan Stream) on the easternmost passes (Schumacher *et al.*, 1982; Stabeno *et al.*, 2002); however, in 1974 when Favorite published his work, the ACC was as yet unknown. Increased understanding of the flow through the passes was documented in a review paper by Stabeno *et al.* (1999).

Unimak Pass (Schumacher *et al.*, 1982; Stabeno *et al.*, 2002) and Amukta Pass (Reed and Stabeno, 1994; 1997) have been sampled fairly extensively in the past, and oxygen and carbon dioxide concentrations were examined in Samalga Pass in the early 1970s (Kelley *et al.*, 1971; Swift and Aagaard, 1976). However, the extensive interdisciplinary dataset collected during the summers of 2001 and 2002 constitutes the first comprehensive, multi-disciplinary examination of the eastern and central Aleutian Passes. These data allow an evaluation of the water properties in and around the Aleutian Passes. The topography of the passes and the width of the North Pacific shelf are dramatically different to the east and west of Samalga Pass. The water properties in the summer of 2001 and 2002 were also very different on either side of this pass. The importance of this result is confirmed by ecosystem differences that are also observed centered on Samalga Pass. This paper describes the spatial patterns observed along the eastern and central Aleutian Islands. We hypothesize about physical mechanisms that may account for the observed spatial patterns.

METHODS

To document the physical and biological components of the marine environment of the eastern and central Aleutian Archipelago, two research cruises were conducted on the R/V Alpha Helix in June 2001 and May-June 2002. The spring bloom generally occurs in May. Thus, the timing of the cruises permitted evaluation of conditions during the summer post-bloom period as well as a limited evaluation of differences between the bloom and the post-bloom periods (in 2002).

Between 7 June and 22 June 2001, 117 CTD (conductivity, temperature, and depth) casts to a maximum depth of ~500 m were taken near the Aleutian Islands. Casts were taken on the north and south side of the Aleutian Islands. In addition, four along-axis, approximately north/south sections (Unimak, Akutan, Amukta, and Seguam Passes) and two across-pass, east/west sections (Seguam and Amukta) detailed the water properties within the passes (Figs. 1,2).

Between 20 May and 18 June 2002, data were collected from 164 CTD casts. Observations were collected in the four passes explored in 2001, and in three other passes (Umnak, Samalga, and Tanaga; Figs. 1,2). In 2002, sampling began in Unimak and Akutan Passes on 20 May (nearly a month earlier than in 2001). The ship then proceeded directly to Tanaga Pass (the westernmost pass sampled). From there, the ship worked its way eastward, finishing up on 19 June in Unimak and Akutan Passes. Visiting Unimak and Akutan Passes at both the beginning and the end of the cruise allowed a comparison of late spring and early summer conditions in the two eastern passes.

In both years, CTD casts were taken with a Seabird SBE-911 Plus system. Salinity calibration samples were taken on all casts and analyzed on a laboratory salinometer. Water samples for dissolved inorganic nutrients (NO_3, NO_2, PO_4, and SiO_4) were collected using 5-liter Niskin bottles. The samples were frozen and stored at -20ºC. Sample analysis was performed at the Pacific Marine Environmental Laboratory using the WOCE protocol (Gordon *et al.*, 1994). Underway surface temperature and salinity were collected with a Sea-Bird Electronics thermosalinograph installed in the ship's seachest. In addition, uncontaminated seawater from this chest was continuously pumped through a fluorometer.

Trajectory data from satellite-tracked drifters that transited through this region are also shown. The drifters were ARGOS buoys with "holey sock" drogues, drogued at 40 m and released upstream of our study location. To avoid trajectories that might be biased by their deployment location, we use only drifter trajectories that crossed 160ºW.

To create images of chlorophyll concentration from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data, we ordered level 1A SeaWiFS files from the Goddard DAAC and processed them with SeaDAS to obtain mapped files of OC4 chlorophyll. We then composited all the files within thirty-day windows. The region is too cloudy to allow shorter time limits.

RESULTS

Properties of the surface waters during both 2001 and 2002 illustrated dramatic spatial variation in the region (Fig. 2). Surface waters on the North Pacific shelf were warmer and fresher than surface waters on the Bering Sea side of the Aleutian Islands. In general, surface waters, particularly on the North Pacific side of the islands, were slightly cooler and saltier in 2002 than in 2001. However, it was impossible to determine whether this difference was due to higher frequency variability (i.e. differences in the tidal cycle sampled), time of year, or interannual variability.

More interesting, however, were the differences within each ocean basin from east to west along the Aleutian chain. Samalga Pass appears to be an important dividing line for water properties along the archipelago. Surface waters were warmer and fresher east of Samalga Pass (Fig. 2). In the North Pacific, sharp fronts associated with both Unimak and Samalga passes were observed in the underway surface salinity (Fig. 3). Surface waters south of the archipelago were freshest east of Unimak Pass (31.4 psu, averaged along-track between 165.1º and 162ºW during the 2001 cruise) due to the influence of the ACC. On the shelf between Unimak Pass and Samalga Pass, the surface salinity averaged 31.9 psu (averaged between 169.4º and 165.1ºW). West of Samalga Pass, surface salinity increased to 32.7 psu (averaged between 169.4ºW and 171.7ºW where the ship crossed through Amukta Pass into the Bering Sea) and was more variable spatially. The surface salinity front associated with Samalga Pass occurred at ~169.4ºW in both 2001 and 2002 and was of similar magnitude in both years according to data from the ship's underway system. A front at Samalga Pass was also observed north of the Aleutian Islands (Fig. 3a; red) suggesting that the fresher water flowing through the eastern passes influenced the surface waters of the Aleutian North Slope Current. Similar patterns (cold, salty, and nitrate-rich west of Samalga Pass as compared to east of the pass) were observed in both years (Fig. 2).

The spatial variation in surface properties between water east and west of Samalga Pass was also found throughout the entire water column. Temperature/salinity/density plots (Fig. 4) illustrate dramatic shifts in water properties from east to west along the south side of the Aleutian Islands. In 2001, the water properties near the Shumagin Islands (east of the Aleutians) were similar to those near Unimak Pass, suggesting that the ACC flows through the Shumagin Islands to Unimak Pass with very little modification. The largest change in salinity and density occurred between those casts taken east of Samalga Pass and those to the west (consistent with the surface salinity front seen in Fig. 3).

Drifter trajectories (Fig. 5) show the different sources for water flowing through Unimak and Samalga Passes from the North Pacific Ocean. Due to the timing of deployment (generally spring through fall in the northern Gulf of Alaska), most of the drifters transited our study region in fall to early winter. The drifters tended to enter the Bering Sea through either Unimak Pass or Samalga Pass and only rarely through any of the other eastern passes. The trajectories are related to the on/off-shelf position at 160ºW; drifters in the shallowest water go through Unimak Pass, drifters in deeper water near the shelf-break transit through Samalga, and drifters offshore of the shelf break continue along in the Alaskan Stream and eventually turn south. (Note one exception where the northernmost drifter at 160ºW transited through Samalga Pass). Drifters located on the shelf illustrated the path of the ACC and moved more slowly than drifters at the shelf-break (Table 2) which showed the path of the Alaskan Stream. Due to high temporal variability and cross-shelf flow, the individual drifter trajectories did not show an obvious spatial separation between the two currents.

Some amount of the flow through Seguam and Amukta Passes is recirculated and cannot be considered inter-basin transport. Both passes are wider (Table 1) than the internal Rossby radius (~ 20 km; Chelton *et al.*, 1998) and therefore have bidirectional flow: northward on the east side and southward on the west side of the passes (Stabeno *et al.*, 2005). Drifter trajectories suggest a clockwise circulation around some of the Islands of the Four Mountains (Fig. 6) east of Amukta Pass. Surface water directly south of the Islands of the Four Mountains and Yunaska Island was colder and saltier (influenced by the Bering Sea) than water south of the passes between these islands. The circulation around the islands was apparently responsible for those patterns observed in the underway temperature (not shown) and salinity data (Fig. 3).

The underway salinity recordings east of Samalga Pass did not exhibit strong differences between regions south of the islands and regions south of the passes, probably because the passes east of Samalga Pass are narrower and have unidirectional northward mean flow. Favorite (1974) noted the occurrence of high salinity water in the North Pacific near 170ºW and attributed it to southward flow from the Bering Sea in the passes west of Samalga, consistent with our results. This suggests that the front in surface salinity near Samalga Pass is persistent and not due to anomalous conditions in 2001 and 2002.

Surface nitrate concentrations also exhibited a significant change at Samalga Pass, with much lower nitrate concentrations to the east of the pass than to the west. Surface nitrate concentrations were highest within the passes (Fig. 2) where strong tidal mixing (Stabeno *et al.*, 2005) brought deep, nitrate rich water to the surface. By mixing phytoplankton out of the euphotic zone, tidal mixing also inhibited primary production (note the low chlorophyll within the passes; Figs. 2,7) that would have drawn down the nitrate. In addition, Mordy *et al.* (2005) show a transition in the nutrient-salinity relationship at Samalga Pass (low salinity and nutrient levels and higher scatter in the nutrient-salinity relationship to the east; higher salinities and nutrients and a tighter relationship west of the pass). They note that the higher variability in the nutrient-salinity relationship east of Samalga Pass was likely due to non-conservative salinities in the eastern region owing to the influence of the ACC.

In both June 2001 and May 2002, chlorophyll fluorescence was much higher (higher chlorophyll concentrations) east of Samalga Pass than west of it. (In June 2002, chlorophyll fluorescence was low throughout the survey region.) In composites (averaged over 1998 to 2002) of chlorophyll concentrations from the SeaWiFS satellite, the highest chlorophyll (Fig. 7) was observed north of the large islands, particularly Umnak and Unalaska Islands, and away from the strong mixing of the passes. The mid-May to mid-June composite (Fig. 7a) shows higher chlorophyll concentrations than later in summer (Fig. 7b). In addition, the spring composite includes less data due to frequent cloudiness over the region during early summer. However, the patterns described are consistent throughout the summer months.

The dramatic change in water properties at Samalga Pass indicates that Samalga Pass was the western limit of the ACC in late spring, with the last of the current turning north through Samalga Pass toward the Bering Sea. The influence of the Bering Sea on the North Pacific and vertical versus lateral mixing within the passes also play a role in defining the observed spatial patterns. On the Bering Sea side of the Aleutians, surface salinities were also fresher east of Samalga Pass (Fig. 2) suggesting that the flow through the eastern passes influenced water properties in the Bering Sea. However, surface temperatures on the Bering Sea side of the Aleutians were much less spatially variable along the island chain than in the North Pacific, suggesting that mixing in the passes and the resulting cooling of the surface layer limited the influence of warm inflows on surface temperatures in the Bering Sea.

Next, we turn our attention to the environment observed in the individual passes. The passes will be described in order from east (Unimak) to west (Tanaga) comparing the passes east of Samalga Pass (referred to as the *eastern* passes) with those to the west of Samalga Pass (the *central* passes). All assessments of oceanographic conditions within the passes must consider strong tidal currents. These currents create strong mixing (and associated fronts) within the passes and displace water to one side or the other depending on the phase of the tide (Stabeno *et al.*, 2005).

Eastern Passes

As mentioned above, the eastern Aleutian Passes (Unimak, Akutan, and Umnak) are much narrower and shallower than those to the west of Samalga Pass (Table 1, Figs. 8-11). This topography influences circulation and mixing within the passes. In addition, the North Pacific shelf is wider east of Samalga Pass than it is to the west (Fig. 1). Thus, the North Pacific shelf-break is farther from the eastern islands and passes than it is from those farther west, affecting the paths of the ACC and the Alaskan Stream and how they modify the Aleutian water properties.

During spring/summer of 2001 and 2002, Unimak Pass, the easternmost pass in the Aleutian Archipelago, exhibited the warmest, freshest water of all of the passes. In each successive pass to the west, temperatures decreased and salinities increased (Figs. 8-11). The southeastern end of the 2001 Unimak Pass section was much warmer and fresher than any of the other sections, exhibiting the influence of the ACC. The southernmost part of the 2001 section was accomplished during a flood (northward) tide resulting in increased ACC influence within the pass. The same region was sampled at the beginning of the ebb tide in 2002. The difference in tidal phase sampled may have accounted for some of the difference between 2001 and 2002. However, the large-scale pattern showed warmer, fresher surface water south of the Aleutian Islands in 2001 compared with 2002 (Fig. 2). Thus, because of their large spatial scale, these differences are more likely due to interannual variability than to a local difference in tidal phase sampled. Current meters in Akutan Pass showed stronger northward flow in June 2001 compared with June 2002 (Stabeno *et al.*, 2005) suggesting that the ACC may have been stronger then, contributing to warmer, fresher conditions in the eastern passes.

All three of the eastern passes exhibited a region of well-mixed water (Figs. 8-13). Out of the five sections (two in 2001 and three in 2002) in the eastern passes, four had regions, spanning 10-20 km in the shallowest part of the pass, that were mixed to the bottom ($25.4 < \sigma_t < 25.6$ kg m^{-3}). The only exception was the Unimak Pass section in 2001, where only the shallowest cast (70 km, 64 m depth, 25.2 kg m^{-3}) was mixed to the bottom (Fig. 8a). This increased stratification may have been due to the timing of the 2001 transect (flood tide and increased ACC influence). The persistence of a mixed region in the eastern passes suggests that the mixing is due to some unrelenting source, probably the strong tides (Stabeno *et al.*, 2005) impinging on the abrupt topography of the passes.

Water properties within the mixed water of the eastern passes showed evidence of lateral mixing between the North Pacific and the Bering Sea. For example, in Unimak Pass in 2001 the mixed water in the center of the pass ($\sigma_t = 25.2$ kg m^{-3} averaged over 64-m deep water column) was denser than the water at the south end of the transect ($\sigma_t = 25.0$ kg m^{-3} averaged over top 65 m) and less dense than the water at the north end of the transect ($\sigma_t = 25.7$ kg m^{-3} averaged over top 65 m). Assuming the top 65 m of the Bering Sea and North Pacific water masses at the ends of the transect mixed together to form the mixed water observed at the center of the transect, the mixed water consisted of 74% Pacific water and 26% Bering Sea water. Note that these percentages depend on the location of the casts chosen as the end members and therefore, are just a rough estimate of the influence of Pacific and Bering Sea water masses on the mixed water. For the eastern pass transects that extended past the Bering Sea shelf-break, the proportions ranged from 50/50 (Umnak) to 74/26 (Unimak).

North of the mixed region, the water column characteristics were more typical of the Bering Sea (colder and saltier) (Figs. 8-11). These surface waters were often denser than bottom waters in the southern part of the passes, implying that the local North Pacific could not have been the sole source of water entering the Bering Sea. The pattern of warm, fresh surface water in the south, well mixed in the passes, and colder, saltier in the north with fronts separating the three regions was typical of all of the sections in the eastern passes.

All three eastern passes had denser, saltier, more nitrate-rich (Figs. 12-13) water near the bottom on the Bering Sea side than at the same depth on the Pacific side. Stabeno *et al.* (2005) show from mooring data that salinity near the bottom at the north end of Akutan Pass becomes saltier (fresher) soon after the tide turns southward (northward). They also show stratified water advecting past the mooring on the ebb tide and mixed water advecting past the mooring on the flood tide suggesting that mixing is occurring south of the mooring location (in the pass). These results suggest that denser, nitrate-rich Bering Sea water was drawn into the passes on the ebb tide, enriching the mixed water in the center of the passes. Surface nitrate levels were elevated in the mixed region in the center of the passes compared to both north and south of the passes. During June, the elevated surface nitrate was not consumed within the passes (probably because the strong tidal and wind energy mixes phytoplankton out of the euphotic zone, suppressing production; Fig. 7). Note that phytoplankton need time (several days) to respond to nutrients and sunlight (e.g. Wilkerson and Dugdale, 1987 and references therein). Thus, as the water moves away from the active mixing of the passes and surface waters begin to stratify, several days may be required before the phytoplankton can respond.

In May 2002, when chlorophyll was abundant, nitrate was depleted in the surface waters over most of Unimak Pass (Fig. 13). Only over the northern sill, where stratification was weak and fluorescence was low, was surface nitrate elevated in May.

Samalga Pass (Transition)

Samalga Pass (sampled between 7 and 9 June 2002) is the transition between the eastern "shelf" passes and the central "oceanic" passes. Its topography (depth and width) and higher stratification are similar to the central passes, but water properties (warmer and fresher) are similar to the eastern passes. Samalga Pass is the first Aleutian Pass with a sill depth greater than 100 m encountered by the westward flowing ACC. Thus, Samalga may be important for the exchange of water between the Gulf of Alaska shelf and the Bering Sea. In addition, the width of the North Pacific shelf decreases near Samalga Pass. East of Samalga Pass, the shelf is wide, separating the coastal current from the Alaskan Stream. However, we have no cross-shelf sections between Unimak and Samalga Passes to show whether a separate ACC and Alaskan Stream exist in this region. West of Samalga Pass, the shelf narrows and the Alaskan Stream (following the shelf break) is closer to the Aleutian Islands. We observed no evidence for a separate coastal current west of Samalga Pass.

Because of weather, the CTD survey of Samalga Pass (Figs. 9d, 11d, 13d) was broken into two segments, both of which were run with the tide flowing from the pass to deeper water (northward flood tide during the northern section, southward ebb tide during the southern section). Thus, there was no opportunity to determine if cold, salty water from depth was drawn into the pass via the tides (as seen in other passes). However, the bottom water in the middle of the pass (at about 32 km, where the section was discontinued) was denser than at the same depth just north and south of that profile (in both sections). The temperature, salinity, and density of these two profiles (~ 32 km) are similar to those in the north end of the pass and are quite different from water properties at the North Pacific end of the pass. Thus, the deep water in the center of the pass appears to be a remnant of deeper water from the north that was pushed up into the pass on a previous ebb tide. Diverging isopycnals at ~ 100-200 m depth (particularly in the southern section) are evidence of mixing/homogenization at depth within the pass. However, the mixing did not extend all the way to the surface (probably because the sill in Samalga is deeper than in the eastern passes), and thus, Samalga was more stratified than the mixed regions of the eastern passes.

Central Passes

Amukta and Seguam Passes were sampled in both 2001 and 2002 while Tanaga was sampled only in 2002. These passes are much deeper and wider than the eastern passes (Table 1; Figs. 8-13). While the small eastern passes are separated by relatively large islands, the larger central passes are separated by small islands (Fig. 1). This topography influences the circulation and mixing in and around the passes and likely plays a role in the differences between the eastern and central passes studied.

In both 2001 and 2002, salinity (Figs. 8-9) was much higher, and temperatures colder (Figs. 10-11), in the central passes than in the eastern passes at the same depth. This was also true for the areas just north and south of the passes. As discussed previously, temperature and salinity differences between the eastern and central passes were largely the result of different source waters: the ACC supplies the eastern passes and the Alaskan Stream supplies the central passes. However, differences in mixing also play a role.

With the exception of Seguam Pass, none of the mixed layers in the central passes reached the bottom (at least in May/June), probably because the passes are deep. However, the topography of the passes does have a major impact on the density structure within the passes. In all three of the central passes, isopycnals had large vertical excursions on the order of 100 – 200 m.

Surface waters of the mixed regions of the central passes were denser than those north and south of the mixed water, illustrating the importance of vertical mixing in these passes. For example, in Seguam Pass in 2002, the surface (and column-averaged) density of the mixed region was 26.6 kg m^{-3} (σ_t) while the ends of the transect exhibited surface densities of 25.6 kg m^{-3} (south) and 26.2 kg m^{-3} (north). The water column on the Bering Sea (North Pacific) end of the pass would have to mix to at least 350 m (500 m) in order to reach densities of 26.6 kg m^{-3}. (The totally mixed region was only ~130 m deep). The along-pass differences in surface density were not as strong in Amukta and Tanaga passes, but showed the same pattern (denser at the center of the pass than at the north and south ends of the transect). The vertical mixing implied by this density structure resulted in colder, saltier, and more nitrate-rich surface water within the central passes than within the eastern passes.

Potential energy relative to the mixed state can be used as an index of stratification (Simpson *et al.*, 1978):

$$PE = \int_{-h}^{0} \left(\rho - \langle\rho\rangle\right) gz \, dz \, ; \qquad\qquad \langle\rho\rangle = \frac{1}{h}\int_{-h}^{0} \rho \, dz$$

where ρ is density and h the depth of the water column. For a vertically mixed system, PE = 0; while PE becomes increasingly negative for increasingly stable stratification. PE is near zero for all of the eastern passes except on the Bering Sea side of the passes where stratification increases (PE decreases) (Fig. 14). With the exception of Seguam Pass, the central passes are not completely mixed even in the shallowest part of the passes (Fig. 14).

Seguam is the shallowest of the central passes and has a very large (30-40 km in 2001; 20 km in 2002) mixed region with well-mixed water in depths shallower than

200 m. In both years, the densest water (2001: 26.85 kg m^{-3}; 2002: 26.75 kg m^{-3}) is observed in a topographic depression (160-165 m depth) in the northern part of the section. North of the pass, water of this density is only observed deeper than ~350 m.

In contrast to the large mixed region observed in Seguam Pass, at Amukta Pass, the water was much more stratified in both 2001 and 2002 (Figs. 8-11, 14). Interestingly, stratification was relatively strong over the shallowest topography of the pass. The weakest stratification was observed in the north end of the pass. In Tanaga Pass as well, stratification was less at mid-depth (200-400 m) north of the pass relative to south of the pass. This may have been due to mixing within the pass combined with advection of the mixed water to the north.

Fresh water distribution, mixing, and uptake by phytoplankton dictate the nutrient distributions in the passes. The lower nutrient levels observed in the eastern passes are associated with fresher (ACC-derived) source water both because of the low nitrate content of the runoff supplying the ACC (Stabeno *et al.*, 2004) and because the increased stratification of the fresher water holds phytoplankton in the surface waters, increasing their access to sunlight and promoting the drawdown of nitrate. By the time the ACC waters reach the eastern Aleutian Passes (sampled in June), the spring bloom on the North Pacific shelf has stripped the water of nutrients.

The central passes, on the other hand, are supplied by the nutrient-rich Alaskan Stream. However, surface nitrate concentrations within the central passes were higher than those observed in the North Pacific waters to the south. Seguam Pass had the highest surface nitrate concentrations in the entire study region in both 2001 and 2002

(Fig. 2). Surface nitrate in the mixed region of Seguam Pass was similar to nitrate concentrations at ~250 m depth north and south of the pass. While Amukta and Tanaga Passes were not mixed top-to-bottom like Seguam, the vertical displacements of isopycnals observed in these passes influenced the distribution of nitrate. Higher nitrate was observed where isopycnals were elevated. Mordy *et al.* (2005) estimated that the nutrient transport through the central passes, enriched via deep mixing, provides enough nutrients for substantial new production in the Bering Sea over the summer.

DISCUSSION

Water properties (temperature, salinity, nutrient concentrations) in the eastern and central Aleutian Passes were examined in June 2001 and May/June 2002. An abrupt change in water properties was observed in the shelf waters of the North Pacific near Samalga Pass. In both periods of observations, surface water was cold, salty, and nitrate-rich west of Samalga Pass compared to east of the pass. Three mechanisms (different source waters, Bering Sea influence, and mixing depth) contribute to the observed spatial patterns of temperature, salinity, and nitrate.

Source Waters

East of Samalga Pass, the North Pacific shelf is wide and the westward flowing ACC exists. The ACC has a strong freshwater core with a strong seasonal cycle (Royer, 1979; Stabeno *et al.*, 1995). The freshest part of the ACC (31.5 psu < salinity < 32.2 psu in 2001; 31.7 psu < salinity < 32.5 psu in 2002) hugs the coastline and turns north to flow through Unimak Pass. The saltier (but still fresher than slope water) offshore portion of the ACC (32.0 psu < salinity < 32.6 psu in 2001; 32.2 psu < salinity < 32.7 psu in 2002) continues to flow southwest along the Aleutians until it reaches Samalga Pass (the first pass deeper than 100m) where it turns north and flows through the pass. In 2001, the water properties at the south end of Unimak Pass were similar to the water properties near the Shumagin Islands upstream (Fig. 4). For comparison, Schumacher and Reed (1986) reported on an October 1977 salinity section across the ACC near the Shumagin Islands with the freshest water (< 31.0 psu) within 25 km of the coast and water at depth (~150-m depth; 50 – 100 km offshore) with salinity up to ~32.8 psu.

Due to the pronounced seasonal cycle of the ACC, the summer observations in the Aleutian passes may not be representative of the entire year. In particular, the maximum freshwater input around the Gulf of Alaska occurs in autumn (Royer, 1982) and the transport in the ACC is weaker in June. While it is possible that the ACC influences passes west of Samalga during its strongest months, salinity measurements from moorings in Akutan and Amukta Passes (Stabeno *et al.*, 2005) suggest that the zonal salinity gradients observed in June hold throughout the year.

West of Samalga Pass, the shelf is too narrow to support a coastal current. Hydrographic sections across the North Pacific shelf west of Samalga Pass show the influence of the Alaskan Stream with no evidence of a separate coastal current (e.g. Reed and Stabeno, 1997; 1999b). With little or no influence from the ACC, the shelf water is much saltier. Thus, the passes from Samalga eastward can be classified as a "coastal" environment with strong influence from the ACC and coastal freshwater discharge. These waters are warmer, fresher, more strongly stratified, and nitrate poor compared with the Aleutian waters west of Samalga Pass. West of Samalga Pass, the marine environment can be classified as "oceanic", with influence from the Alaskan Stream.

Advection from the Bering Sea

Many of the passes from Samalga Pass westward have widths (Table 1) greater than the internal Rossby radius (~ 20 km, Chelton *et al.*, 1998). This results in northward flow on the east and southward flow on the west side of the wider passes (Stabeno *et al.*, 2005). The southward flow is partially derived from North Pacific waters through retroflection of the northward current and/or clockwise circulation around the island defining the western side of the pass (see Fig. 6). However, it mixes with Bering Sea water along its path which results in the advection of colder, saltier water south into the North Pacific from the Bering Sea. In both 2001 and 2002, CTD data were collected from transects oriented roughly east/west across Amukta Pass (not shown) in addition to the along-axis transects shown in Figs. 8-13. In both years, water in the top 100 m averaged 0.23 psu saltier in the westernmost cast (region of mean southward flow; Stabeno *et al.*, 2005) than in the easternmost cast. Thus, due to their width, the central passes allow some influence from the Bering Sea to the North Pacific, while the eastern passes allow primarily one-way influence (in the mean) from the North Pacific to the Bering Sea.

Depth of Mixing

The passes east of Samalga Pass are longer along-axis (farther removed from the deep waters of either the Pacific or the Bering Sea) and shallower. Water properties within the mixed water of the eastern passes show evidence of lateral mixing between the shallow waters of the North Pacific and the Bering Sea.

The central passes are shorter and deeper, allowing more influence from the deeper waters of the Bering Sea. Surface densities of the mixed water regions of the central passes were denser than surface densities north and south of the mixed water, implying the importance of vertical mixing in defining the water properties of the mixed water in the central passes. This vertical mixing resulted in colder, saltier, and more nitrate-rich surface water within the central passes than within the eastern passes.

Ecosystem patterns

The spatial pattern in the physical data is reflected in ecosystem patterns. In a study of Steller's sea lion diets derived from scats collected from 1990-1998, Sinclair and Zeppelin, 2002) found that Steller's sea lion diets east of Samalga Pass were more diverse (with walleye pollock the primary prey), whereas, west of Samalga Pass, diets were less diverse and heavily dominated by Atka mackerel. In addition, the population trends in non-pup Steller's sea lions have been significantly negative in the central Aleutian Islands and relatively stable in the eastern Aleutian Islands (Loughlin and York, 2000) with Samalga Pass as the dividing line. Seabird (Jahncke *et al.*, 2005) and zooplankton (Coyle, 2005) species distributions also partition at Samalga Pass. Understanding the mechanisms underlying these spatial patterns is necessary to understanding the ecosystem as a whole and moving towards predictive capabilities.

All of the data presented here are consistent with the following scenario: Tidal currents within the passes are very strong (fluctuating between northward and southward flow of order 1.0 m s^{-1} with significant velocities throughout the water column; Stabeno *et al.*, 2005). The combination of strong tidal currents and abrupt topography within the passes results in mixing. In the shallow eastern passes, the entire water column is homogenized in the center of the passes. In the deeper central passes, the deeper water column shows evidence of mixing but homogenization rarely occurs over the entire water column. Seguam Pass (with the strongest currents > 250 cm s^{-1}; Stabeno *et al.*, 2005), the shallowest central pass, is the exception with a large region of top-to-bottom homogenization. However, as discussed above, even though the water column in the central passes is rarely well-mixed, some mixing does occur and the surface waters in the center of the passes are influenced by the deeper waters of the Bering Sea.

Because the shelf is wider on the Pacific side of the island chain, the deep water pushed into the passes from the Bering Sea on the ebb tide may have relatively more influence on the mixed water column than deep water from the Pacific. Thus, nutrients introduced into the surface layer with the Bering Sea deep-water result in higher surface nutrient concentrations within the passes. However, productivity within the passes is inhibited due to the strong mixing. The net flow through the passes is northward (Stabeno *et al.*, 2005), transporting the newly mixed, high nutrient surface water into the Bering Sea. As this water moves away from the strong mixing of the passes and becomes more stratified, phytoplankton can take advantage of the enhanced nutrient concentrations. Thus, the northern side of the Aleutian Islands (especially in the lee of the islands) appears to be the more productive (Fig. 7).

The observations discussed here resulted in substantial gains in our understanding of the oceanography of the Aleutian Passes. However, little information on the seasonal cycle or interannual variability can be obtained from measurements taken in the summers of two years. The moored measurements discussed by Stabeno *et al.* (2005) provide some seasonal context, but to better understand how typical these two years were and how the processes discussed here may vary over time, observation programs in the Aleutians must continue.

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FIGURES

Figure 1. Map of eastern and central Aleutian Islands. Passes discussed in text are noted by white lines. Currents are noted by black arrows. Water depth is color coded from light blue (shallow) to dark purple (deep).

Figure 2. Surface water properties (denoted by colored dots) during 2001 and 2002. Sea surface temperature (ºC), Salinity (psu), Nitrate (μmol kg^{-1}).

Figure 3. Underway sea surface salinity (psu) during the 2001 cruise. a) salinity plotted against latitude, south of Aleutian Islands (black) and north of islands (red). b) salinity represented by colored line on map. Average along-track salinities in the regions (south of the Aleutian Islands) east of Unimak Pass, between Unimak and Samalga Passes, and between Samalga Pass and Amukta Pass are noted. (Data from the 2002 cruise exhibited similar patterns.)

Figure 4. Temperature/salinity plots from (a) 2001 and (b) 2002. Black contours indicate density. (c) and (d) show color-coded locations of CTD casts used in the T/S plots. All casts east of Samalga Pass are shallower than 122 m (all but 2 are shallower than 100 m). For casts west of Samalga Pass, the T/S plot is green (surface – 100 m) and light blue (deeper than 100 m).

Figure 5. Drifter trajectories for all drifters that crossed 160ºW in 2001 and 2002. Colors indicate which pass they transited (blue: Unimak or Akutan, red: Samalga or Islands of the Four Mountains, green: none).

Figure 6. Drifter trajectories for four drifters that circuited some of the Aleutian Islands. All drifters circled the islands in a clockwise direction.

Figure 7. Chlorophyll (mg m^{-3}) averaged over (a) mid-May to mid-June and (b) mid-August to mid-September, 1998 – 2002 from the SeaWiFS satellite. Color scale is the same for both panels. Regions with no data (due to clouds) are shown in white.

Figure 8. Salinity (psu; color) in the along-pass transects in 2001. Density is denoted by black contours. Distance along horizontal axis (km) is measured from the northernmost cast in the transect.

Figure 9. Salinity (psu; color) in the along-pass transects in 2002. Density is denoted by black contours. Distance along horizontal axis (km) is measured from the northernmost cast in the transect.

Figure 10. Temperature (ºC; color) in the along-pass sections in 2001. Density is denoted by black contours. Distance along horizontal axis (km) is measured from the northernmost cast in the transect.

Figure 11. Temperature (ºC; color) in the along-pass transects in 2002. Density is denoted by black contours. Distance along horizontal axis (km) is measured from the northernmost cast in the transect.

Figure 12. Nitrate (μmol kg^{-1}; colored dots) in the along-pass transects in 2001. Density is denoted by black contours. Distance along horizontal axis (km) is measured from the northernmost cast in the transect.

Figure 13. Nitrate (μmol kg^{-1}; colored dots) in the along-pass sections in 2002. Density is denoted by black contours. Distance along horizontal axis (km) is measured from the northernmost cast in the transect.

Figure 14. Potential energy (J m^{-2}) relative to the mixed state. See text for method of calculation. Distance along horizontal axis (km) is measured from the northernmost cast in the transect.

TABLES

Table 1. Characteristics of passes through the Aleutian Archipelago investigated in this study. (Cross-sectional area is a rough estimate due to inadequacy of bathymetry data in these narrow passes.)

	Central Passes			Transition	Eastern Passes		
	Tanaga	Seguam	Amukta	Samalga	Umnak	Akutan	Unimak
Width (km)	32	30	68	29	7	7	19
Depth (m)	235	165	430	200	60	30	52
Cross-sectional area (km^2)	5.3	4.4	24.4	6.7	0.5	0.1	1.0

Table 2. Drifter speeds (averaged between 160ºW and 164ºW) calculated from the drifter trajectories shown in Fig. 5. Average speed calculated for the four Samalga drifters (red) was not significantly different from that calculated for the eight Stream drifters (green).

	Mean Speed ($m\ s^{-1}$)	Maximum Speed ($m\ s^{-1}$)	Minimum Speed ($m\ s^{-1}$)	Number of Drifters
Unimak (blue trajectories)	0.14	0.34	0.05	9
Samalga and Stream (red and green trajectories)	0.36	0.93	0.14	12

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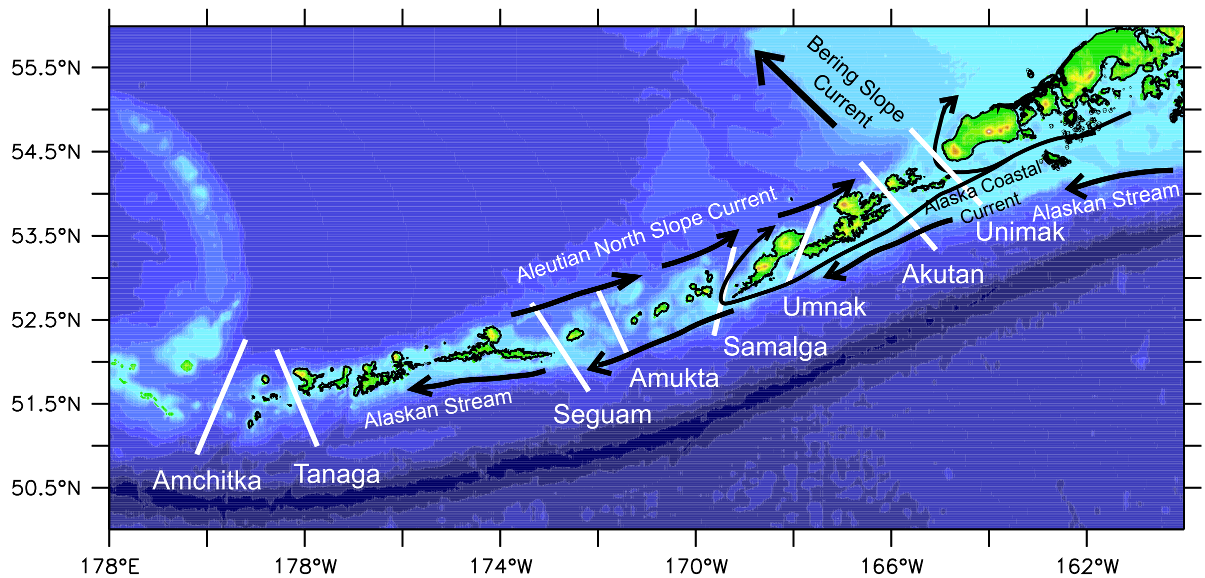


55.5°N
54.5°N
53.5°N
52.5°N
51.5°N
50.5°N
178°E
178°W
174°W
170°W
166°W
162°W
Bering Slope Current
Aleutian North Slope Current
Alaska Coastal Current
Alaskan Stream
Alaskan Stream
Unimak
Akutan
Umnak
Samalga
Amukta
Seguam
Tanaga
Amchitka

Fig. 1

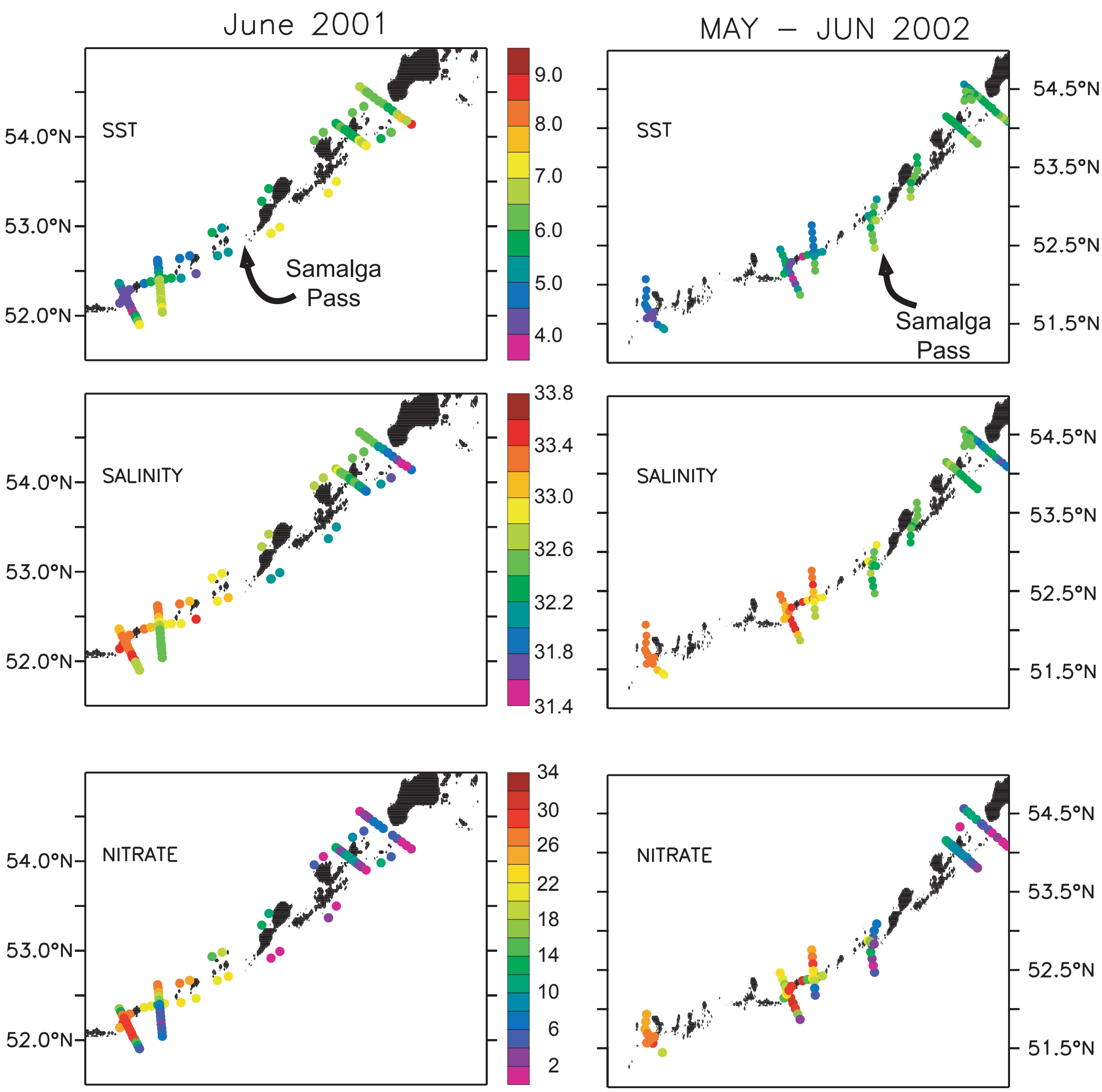
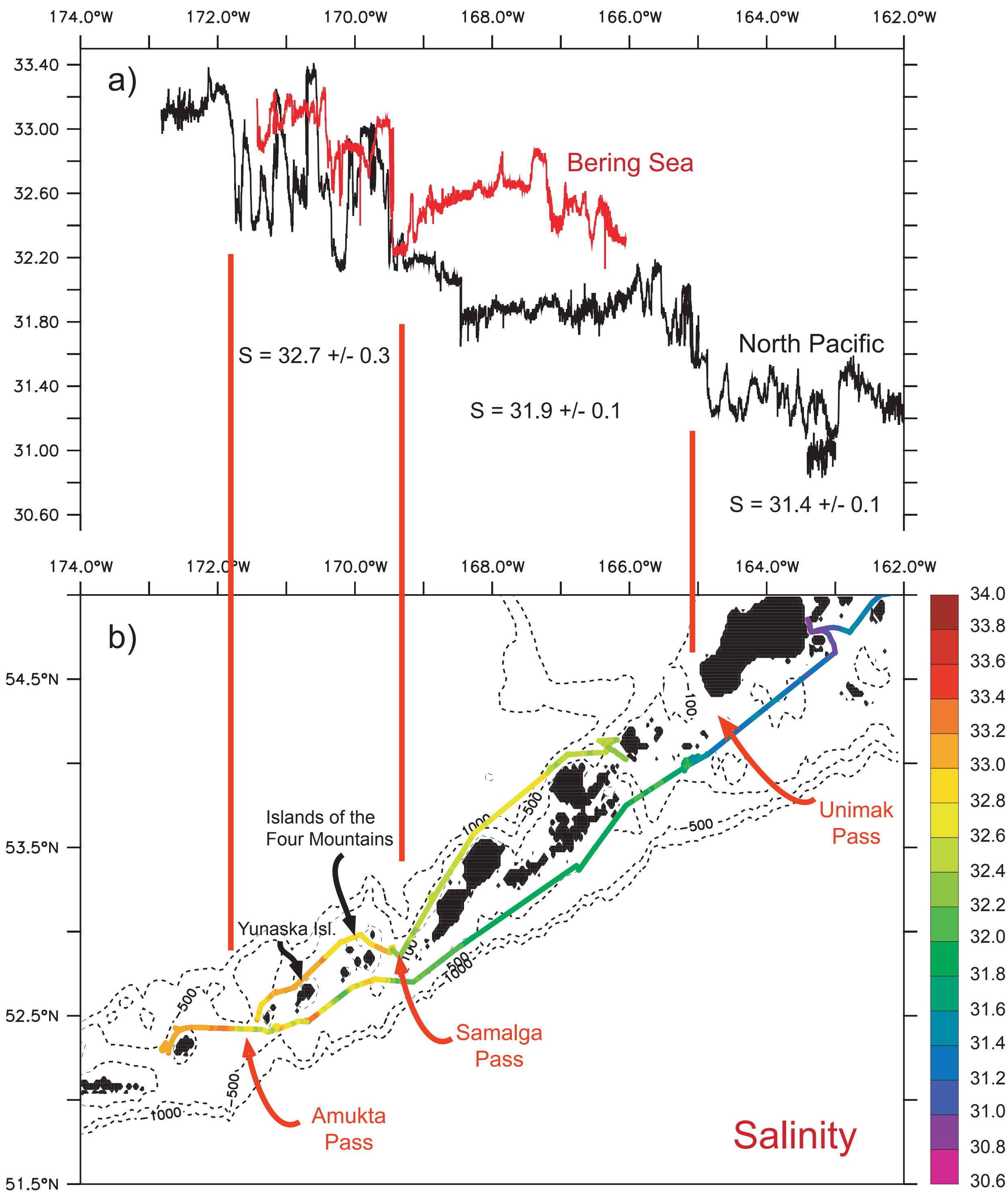
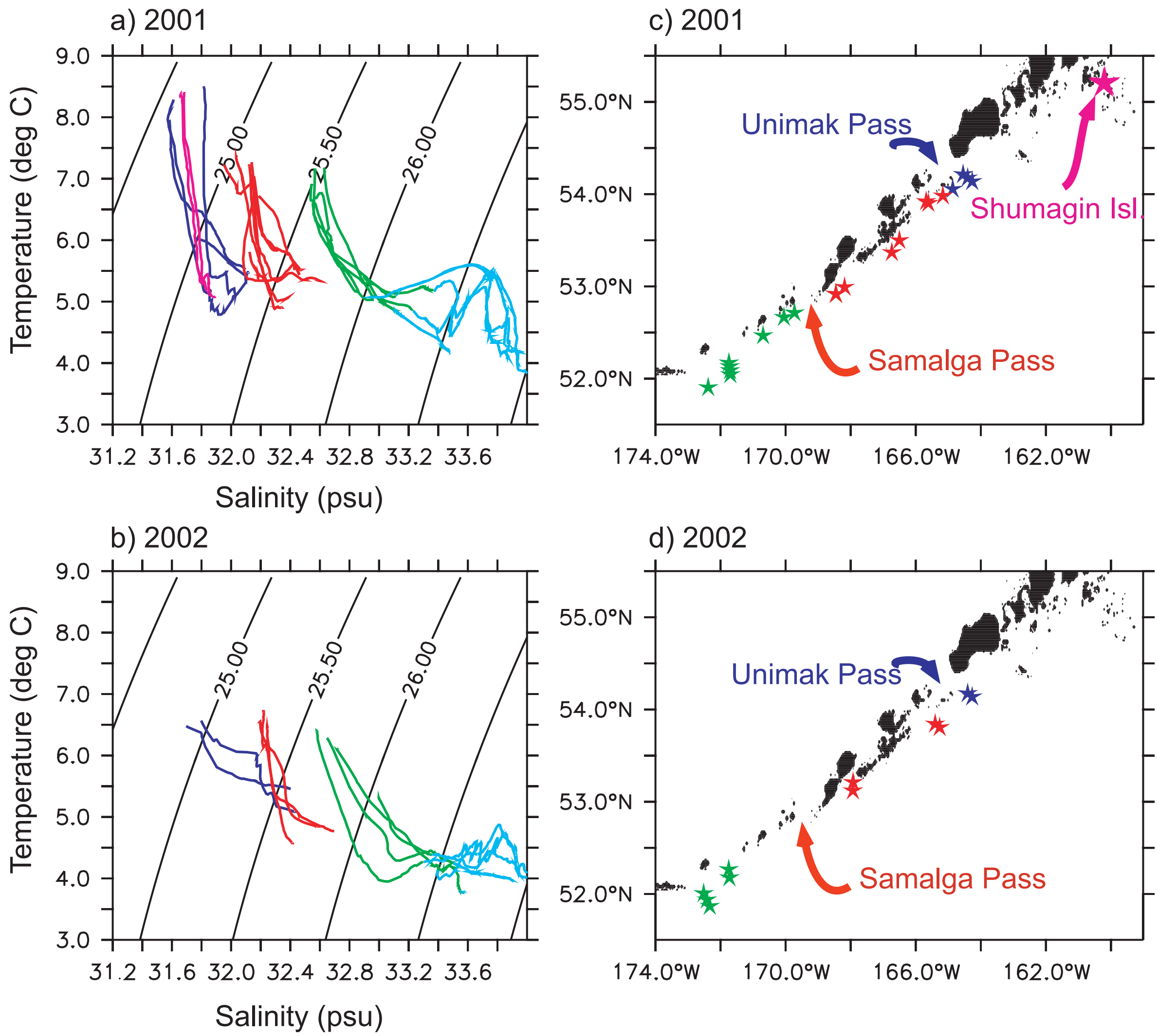

June 2001
MAY – JUN 2002
SST
SALINITY
NITRATE
Samalga Pass
Samalga Pass
54.0°N
53.0°N
52.0°N
54.5°N
53.5°N
52.5°N
51.5°N
9.0
8.0
7.0
6.0
5.0
4.0
33.8
33.4
33.0
32.6
32.2
31.8
31.4
34
30
26
22
18
14
10
6
2

Fig. 2



174.0°W
172.0°W
170.0°W
168.0°W
166.0°W
164.0°W
162.0°W
33.40
33.00
32.60
32.20
31.80
31.40
31.00
30.60
a)
Bering Sea
North Pacific
S = 32.7 +/- 0.3
S = 31.9 +/- 0.1
S = 31.4 +/- 0.1
b)
54.5°N
53.5°N
52.5°N
51.5°N
Islands of the
Four Mountains
Yunaska Isl.
Unimak
Pass
Samalga
Pass
Amukta
Pass
Salinity
100
500
1000
34.0
33.8
33.6
33.4
33.2
33.0
32.8
32.6
32.4
32.2
32.0
31.8
31.6
31.4
31.2
31.0
30.8
30.6

Fig. 3


a) 2001
b) 2002
c) 2001
d) 2002
Temperature (deg C)
Salinity (psu)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
31.2
31.6
32.0
32.4
32.8
33.2
33.6
25.00
25.50
26.00
55.0°N
54.0°N
53.0°N
52.0°N
174.0°W
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162.0°W
Unimak Pass
Shumagin Isl.
Samalga Pass

Fig. 4

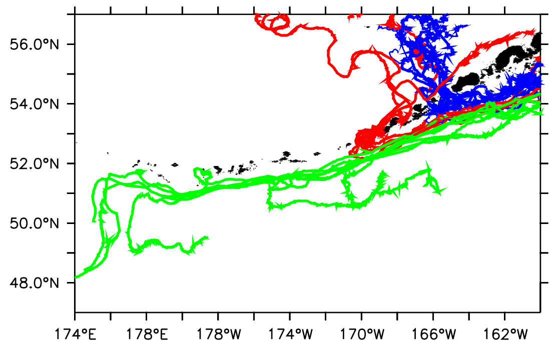
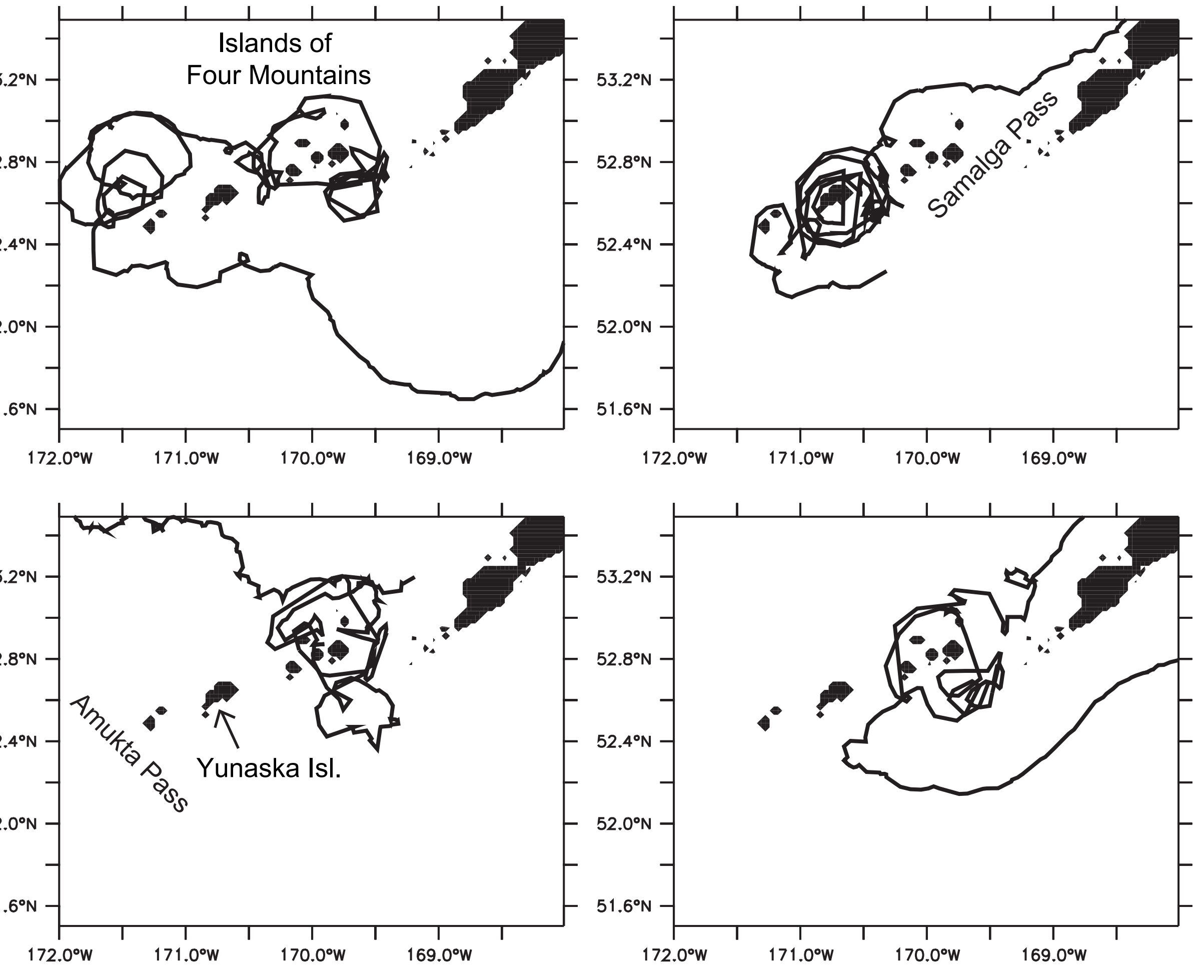


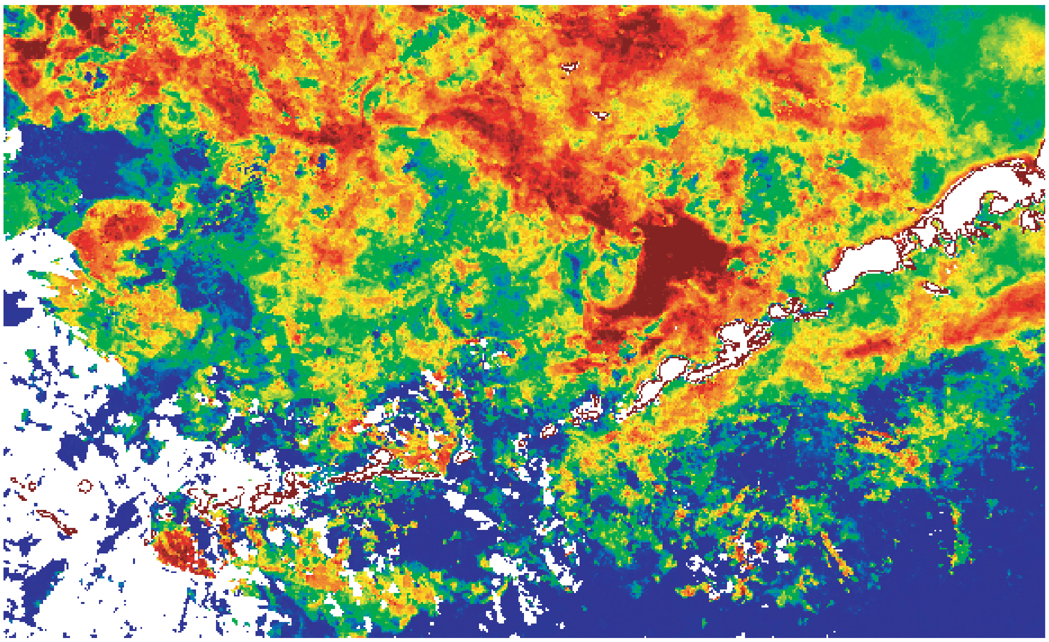
Fig. 5



Islands of Four Mountains
Samalga Pass
Amukta Pass
Yunaska Isl.
53.2°N
52.8°N
52.4°N
52.0°N
51.6°N
172.0°W
171.0°W
170.0°W
169.0°W

Fig. 6

(a) mid May - mid June composite (1998-2002)



(b) mid August - mid September composite (1998-2002)

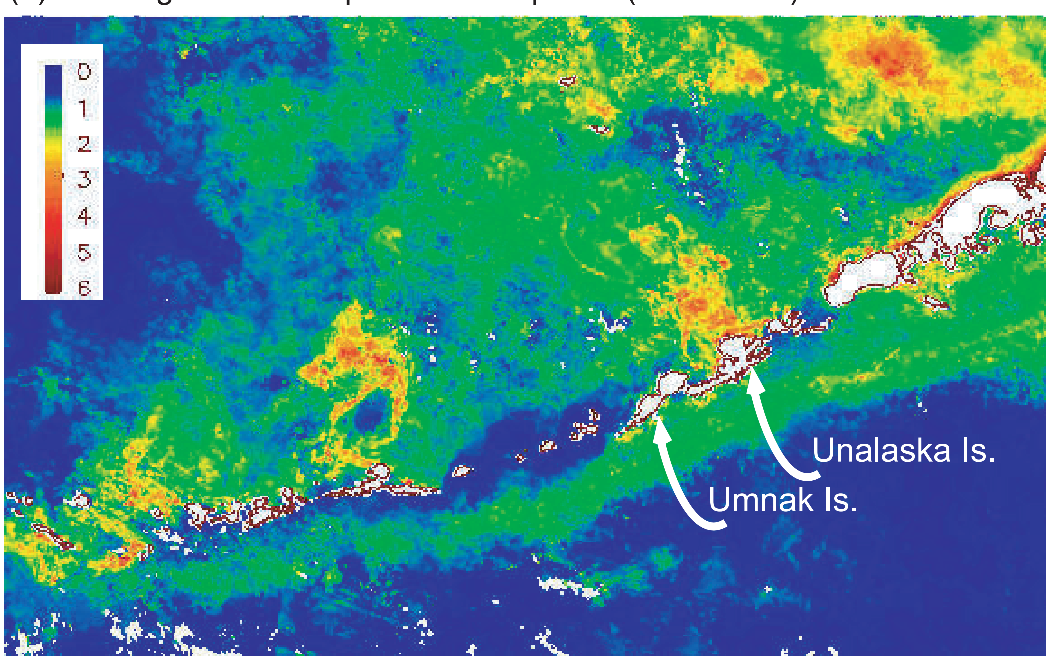
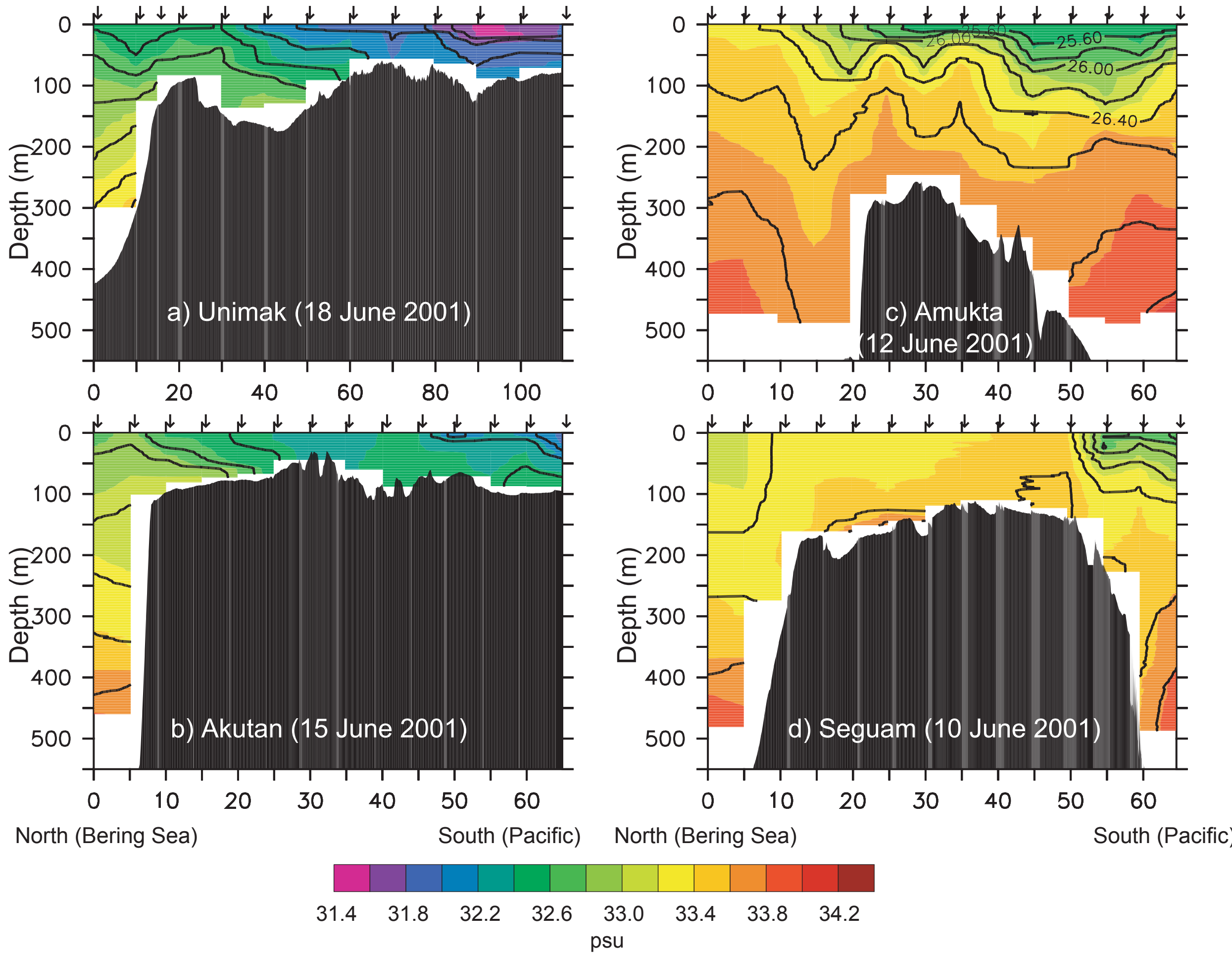


Fig. 7



a) Unimak (18 June 2001)
b) Akutan (15 June 2001)
c) Amukta
(12 June 2001)
d) Seguam (10 June 2001)
Depth (m)
North (Bering Sea)
South (Pacific)
25.60
26.00
26.40
31.4
31.8
32.2
32.6
33.0
33.4
33.8
34.2
psu

Fig. 8

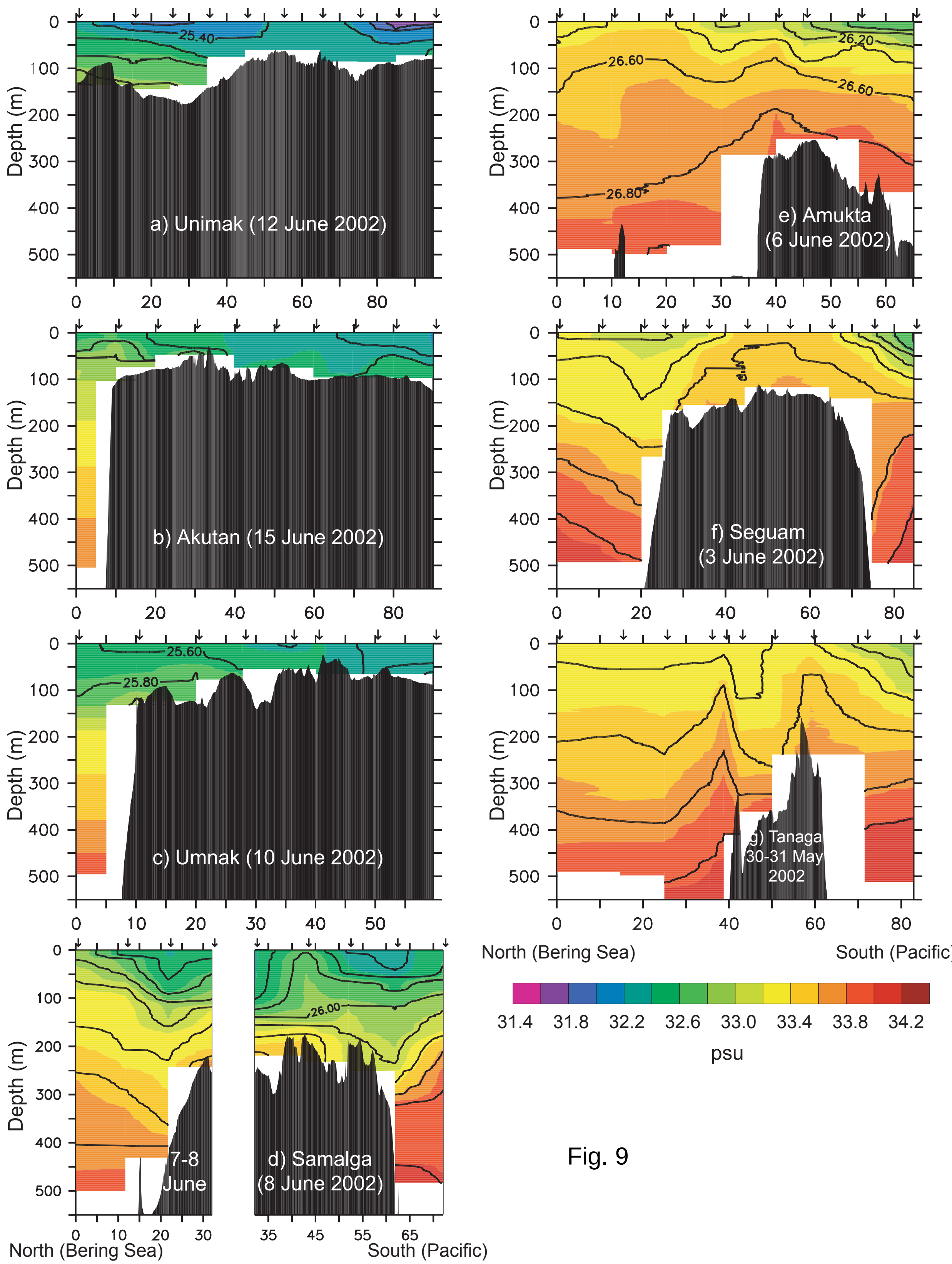

Depth (m)
a) Unimak (12 June 2002)
25.40
b) Akutan (15 June 2002)
c) Umnak (10 June 2002)
25.60
25.80
7-8
June
d) Samalga
(8 June 2002)
26.00
North (Bering Sea)
South (Pacific)
e) Amukta
(6 June 2002)
26.20
26.60
26.80
f) Seguam
(3 June 2002)
g) Tanaga
30-31 May
2002
31.4
31.8
32.2
32.6
33.0
33.4
33.8
34.2
psu

Fig. 9

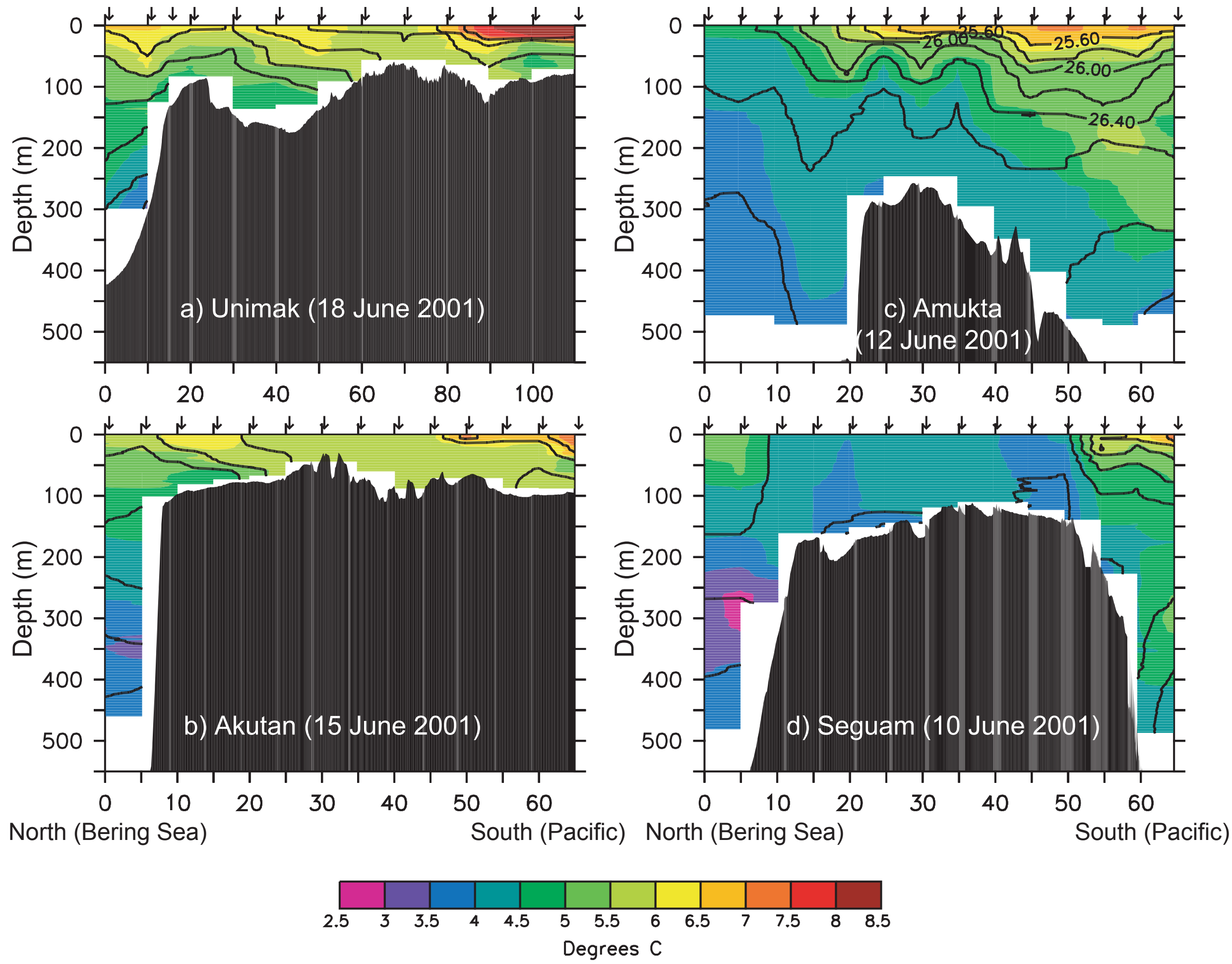

a) Unimak (18 June 2001)
b) Akutan (15 June 2001)
c) Amukta (12 June 2001)
d) Seguam (10 June 2001)
Depth (m)
North (Bering Sea)
South (Pacific)
25.60
26.00
26.40
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
Degrees C

Fig. 10

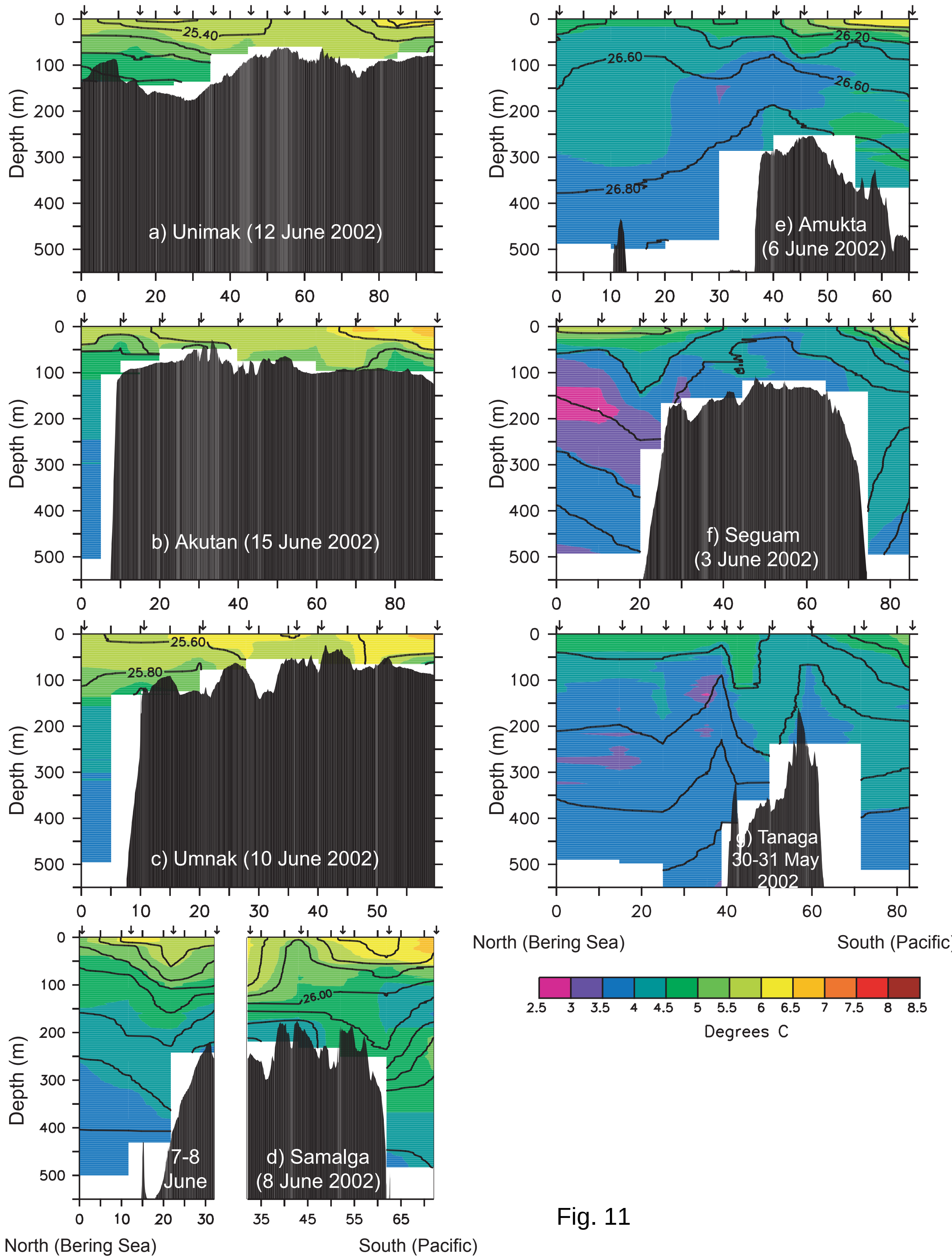
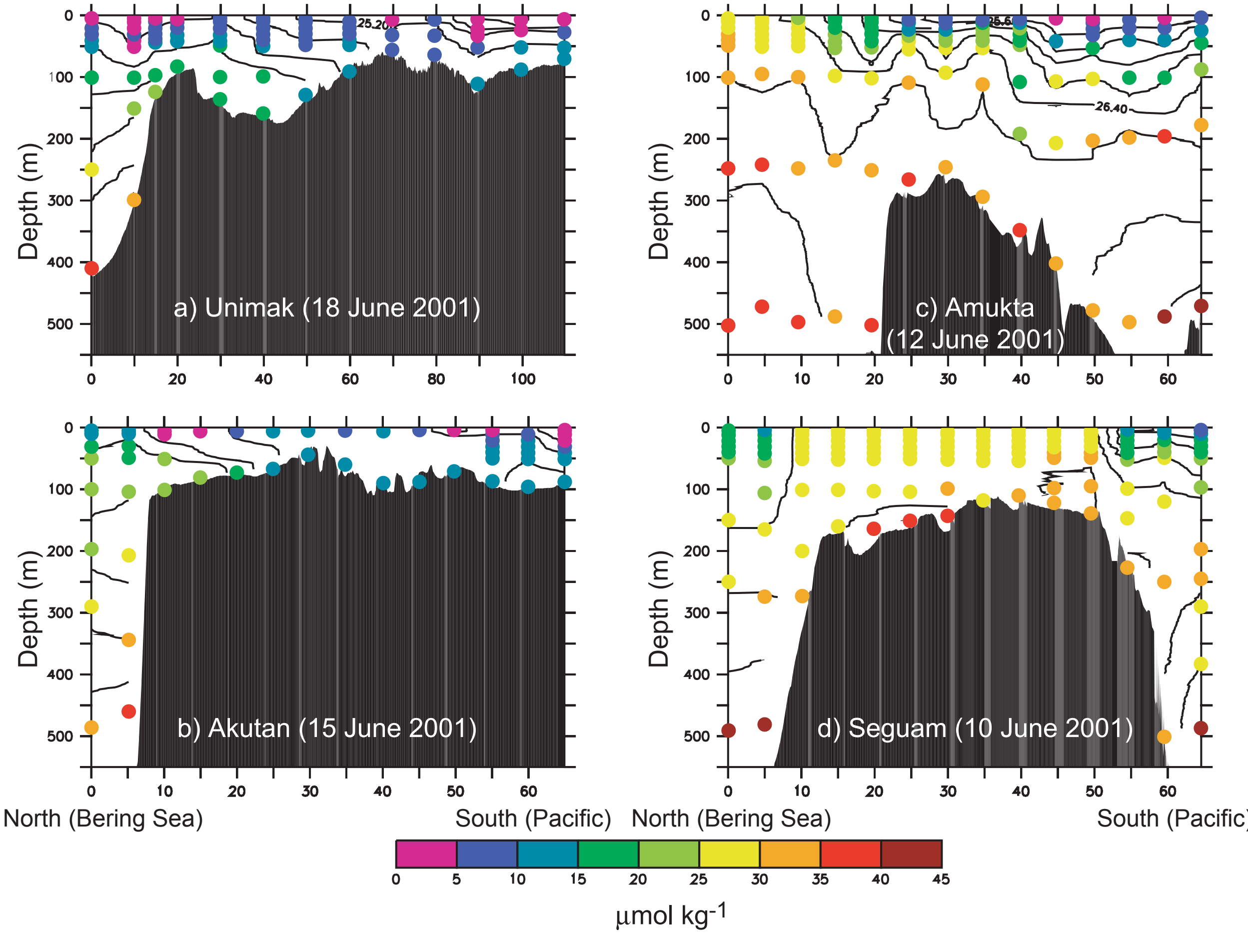

a) Unimak (12 June 2002)
25.40
e) Amukta
(6 June 2002)
26.20
26.60
26.60
26.80
b) Akutan (15 June 2002)
f) Seguam
(3 June 2002)
c) Umnak (10 June 2002)
25.60
25.80
g) Tanaga
30-31 May
2002
7-8
June
d) Samalga
(8 June 2002)
26.00
Depth (m)
North (Bering Sea)
South (Pacific)
Degrees C
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5

Fig. 11



a) Unimak (18 June 2001)
b) Akutan (15 June 2001)
c) Amukta (12 June 2001)
d) Seguam (10 June 2001)
Depth (m)
North (Bering Sea)
South (Pacific)
µmol kg-1

Fig. 12

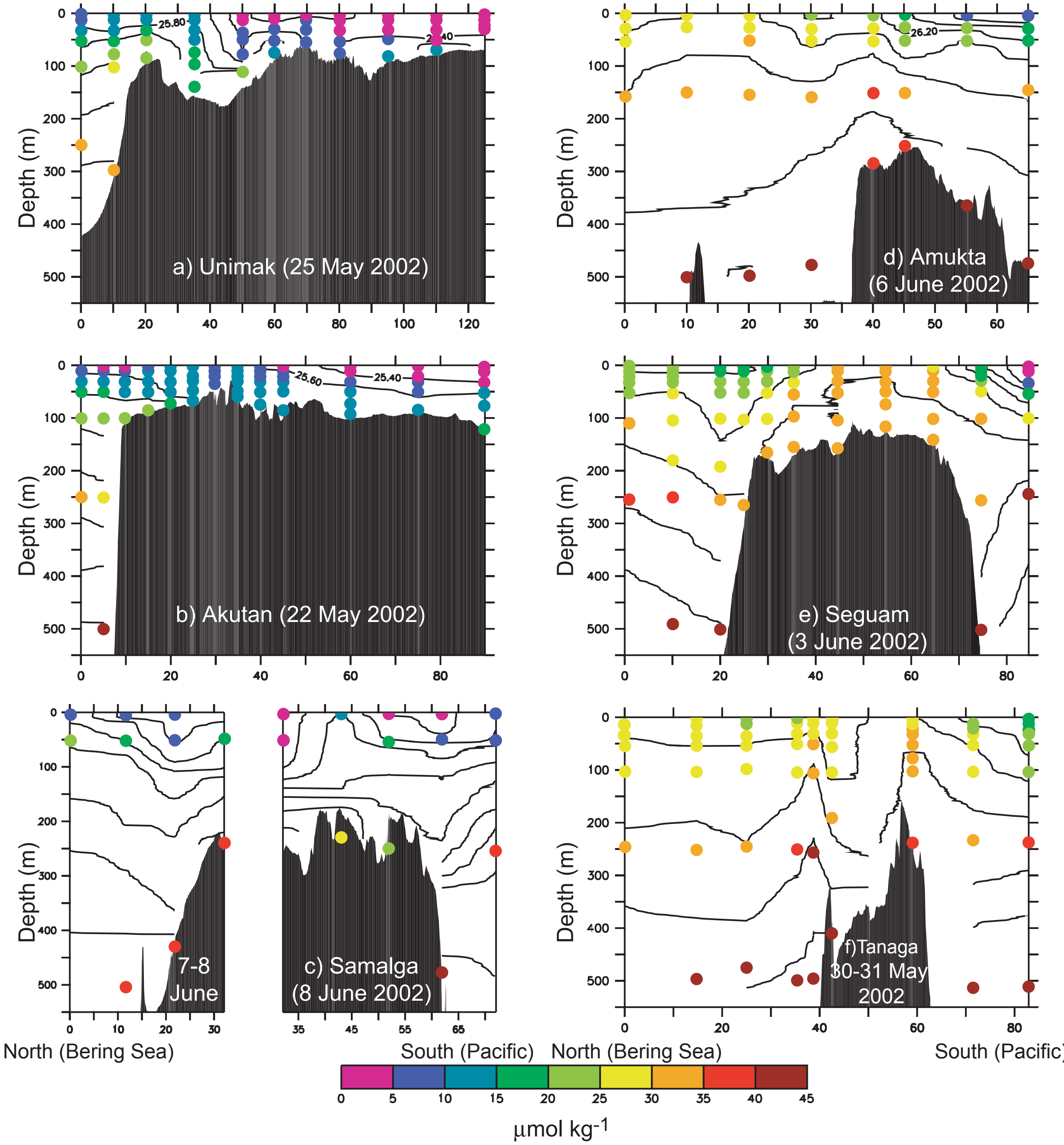
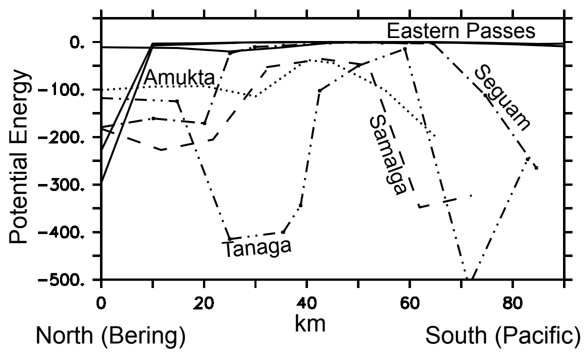

a) Unimak (25 May 2002)
b) Akutan (22 May 2002)
c) Samalga (8 June 2002)
7-8 June
d) Amukta (6 June 2002)
e) Seguam (3 June 2002)
f)Tanaga 30-31 May 2002
Depth (m)
North (Bering Sea)
South (Pacific)
µmol kg-1

Fig. 13



Eastern Passes
Amukta
Seguam
Samalga
Tanaga
Potential Energy
0.
-100.
-200.
-300.
-400.
-500.
0
20
40
60
80
km
North (Bering)
South (Pacific)

Fig. 14